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14. ABSTRACT

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Thrust Stand Micro-Mass Balance Diagnostic Techniques for the Direct Measurement of Specific Impulse (Preprint)

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Abstract

A technique has been developed to directly measure the specific impulse from pulsed thruster systems. The technique is especially useful for propulsion devices that utilize solid propellants where a direct measurement of the propellant mass flow is extremely difficult. A torsion balance is used with a horizontal axis of rotation. A thruster is placed on the balance such that the impulse of the thruster firing and the change in mass due to the expending of propellant act in the same direction. The coupled force measurements can then be decoupled to assess the ratio of the impulse to the weight of propellant expended, also known as the specific impulse. A model has been developed to show the utility of the technique for pulsed systems with a firing time less than the natural period of the balance. In this study, a laser ablation thruster using Buna, Viton and Teflon propellants was investigated. Specific impulse measurements on the order of 200 sec have been demonstrated with the laser ablation thruster.

Introduction

The impulse produced by a thruster can be found by integrating the thrust produced with time. The specific impulse, Isp, is defined as the impulse delivered by a propulsion system divided by the weight of the propellant used to produce that impulse.[1] Traditional specific impulse measurements for propulsion systems that use solid propellants are complicated by several issues. First, the amount of mass loss and the associated impulse provided by pulsed

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systems may be relatively low requiring the averaging of multiple thruster firings to obtain meaningful data. The performance of individual pulses can be lost through the averaging of multiple tests. Understanding of individual pulse performance can lead to more efficient thrusters if parameters between subsequent tests can be quantified. Second, the system mass is traditionally measured before the performance measurements, and again after, to assess the propellant mass used.[2] These measurements may take place days apart and may require the system to be put into vacuum and removed from vacuum in between thruster firings at the cost of valuable resources. Finally, issues of contamination, oxidation and adsorption may complicate mass measurements that are not done in-situ.

To combat these issues for pulsed thruster systems, a Thrust Stand Mass Blance (TSMB) and associated experimental techniques have been developed where both the total mass loss and impulse are measured simultaneously. The concurrent measurement of the impulse and mass loss leads to a direct measure of specific impulse. The benefits of the developed technique include the ability to measure specific impulse in-situ and directly without the complications and potential inaccuracies of multiple measurements. The resolution of the TSMB is such that it can measure impulse and mass loss of individual pulses from most thruster systems currently under development. The developed technique allows both mass and impulse measurements simultaneously while the thruster is in vacuum reducing the influence of oxidation, adsorption and contamination. The major limitation of the technique is that it is only currently valid for pulsed systems where the pulsewidth is less than the natural period of the thrust stand.

The technique has been applied in this work to investigate a laser ablation system although the technique is also valid for a variety of pulsed propulsion systems such as solid microthrusters[3] and pulsed plasma thrusters.[4] Laser ablation affords some benefits when developing the TSMB. First, the laser pulse energy can be tuned to allow more or less ablative mass loss in a particular laser pulse. Second, a variety of propellant (target material) can be used to assess the techniques ability to distinguish the specific impulse over a relatively wide range. One of the disadvantages to using laser propulsion is the inherent scatter in the data between pulses. Drift in the laser energy output and physical differences between ablation sites on engineering targets account for much of the scatter. However, this scatter can also be viewed as a benefit in the development of this system since the ability to measure the performance of individual pulses can be demonstrated.

Numerous experimental techniques have been employed in the past to measure mass loss and other fundamental properties of laser ablation events. The techniques include time-of-flight mass spectroscopy, plasma spectroscopy, ns-shadowgraphy,[5] and other plasma imaging techniques.[6] Each technique may be useful in understanding certain aspects as they monitor specific components of the ejected material. However, each has limitations and weaknesses in their application for investigating a broad range of mechanisms for laser ablation. As the ejected material is expected to contain particles of different sizes, charged and neutrals particles, and particles of varying velocity, it is difficult to simultaneously capture all components to accurately determine the amount of mass lost. By only monitoring some portions of the ablated material, it is often possible to underestimate the mass loss, which generally results in overestimating the specific impulse.

Thrust Stand Mass Balance

The TSMB is based on the nano-Newton-second impulse balance system (NIBS) described by D'Souza and Ketsdever.[7] By inverting the NIBS to allow for a horizontal axis of rotation, both the impulse and the change in mass from the propulsive event provide forces acting in the same direction, as illustrated in Figure 1. In this system, the weight of the propulsion system acts as a steady state force on the TSMB. As a thruster fires, mass is released and the propulsion system gets lighter, with the change in mass resulting in a measurable deflection of the TSMB. The resulting steady deflection is calibrated to indicate the net change in mass due to the loss of propellant. With both the impulse force and mass loss force acting in the same direction, the two forces couple to produce a single deflection trace on the TSMB. In order for the performance of the thruster to be quantified, each component must be resolved individually from the single deflection trace. To assess the feasibility of such an analysis, a model was created to simulate the behavior of the TSMB.

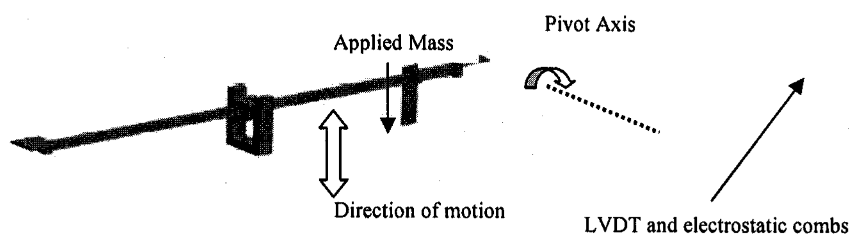


Figure 1: Schematic of the TSMB setup and configuration.

The TSMB model is based directly on the NIBS model discussed by D'Souza and Ketsdever.[7] The model takes the force profile for each component (impulse and weight change) and plots their individual and combined dynamic effects on the TSMB. It has already been shown that any arbitrary or irregular force can be approximated using a series of constant force segments of small time widths $d\tau$.[7] As such, the combined effect of two overlapping forces does not pose a particular problem for the TSMB. For simplicity, a constant force **F** is applied for a duration of τ, resulting in the modeling of a constant impulse. The force profile corresponding to the mass change can be determined for a given specific impulse such that the weight loss is given by the total impulse ($\mathbf{F} * \tau$) divided by the specific impulse. Assuming the mass loss occurs steadily over the duration of the impulse, the force profile for the mass loss ramps up to a plateau as seen in Figure 2.

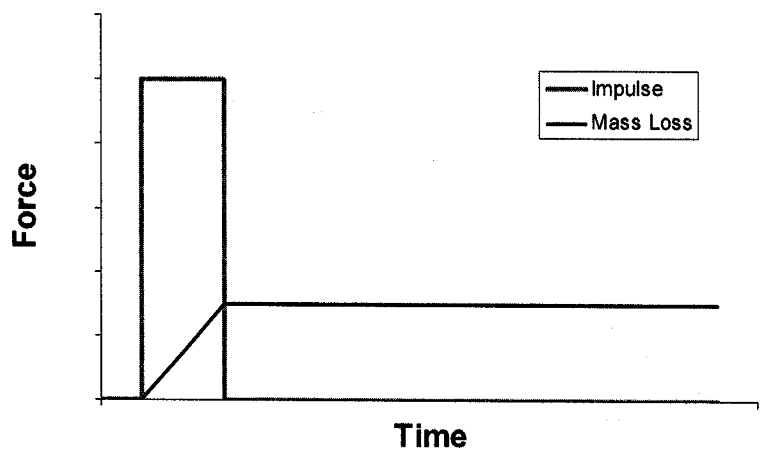
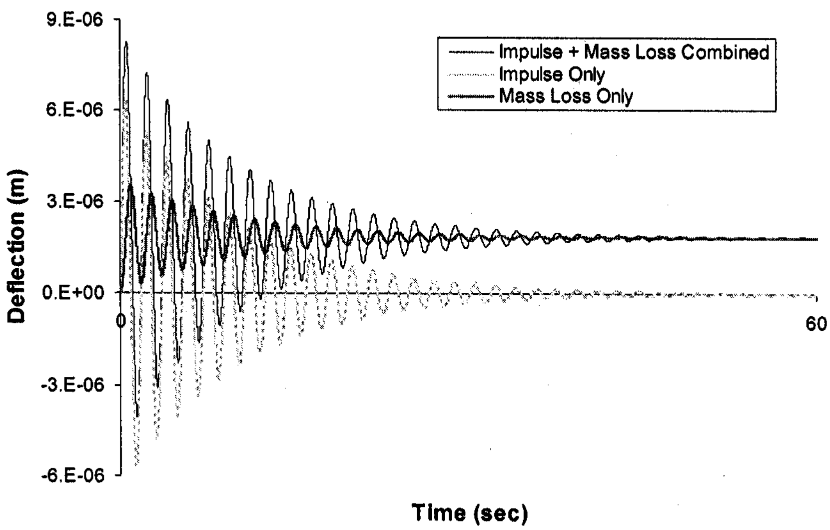


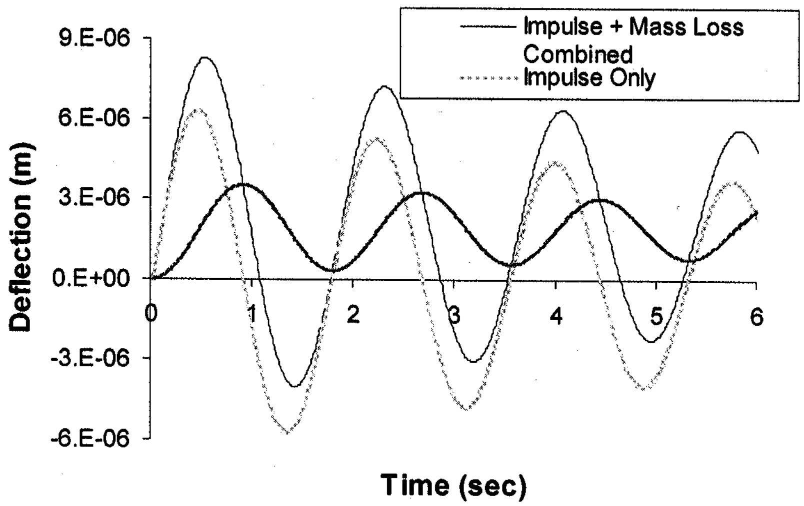
Figure 2: Force profiles for an impulse and its corresponding mass loss.

Figure 3a shows results from the TSMB model for a simulated pulsed thruster delivering a typical impulse of 1 mN-sec. Shown are traces for the dynamic response of each force individually and their combined result on the TSMB. The individual force traces assume that the TSMB has experienced only that force in the absence of the second force. It is evident in Fig. 3b that between the individual impulse trace and mass loss trace, a phase shift exists in the timing, which results from the accommodation of the stand to the effective natural period of oscillation. In the

case of the impulse, the pulsewidth is short relative to the natural period of the TSMB that the stand accommodates almost instantaneously. However for the mass loss, the force is continuously applied. This manifests as a slight phase shift in the two individual effect curves, that when combined, results in a curve that is very close in magnitude to the impulse alone but temporally shifted. Due to the fact that the impulse is measured by taking the range of deflection from the first peak to the first valley, the magnitude of the impulse alone tends to be preserved in the combined trace. The mass loss is then simply measured by examining the total deflection of the tail of the trace compared to the initial zero point.



(a)



(b)

Figure 3: (a) Individual impulse and mass loss traces generated by model simulation. (b) Enlarged portion of traces.

In order to verify that the magnitude of the impulse is preserved and can be decoupled from the mass loss, the input parameters of pulsewidth, specific impulse, and total impulse were varied in the model. The total impulses were varied from 3 nN-sec up to 1mN-sec to fully cover the dynamic range of the stand as limited by the TSMB's sensitivity. This entire impulse range was generated using a wide range of pulsewidths, all less than the natural period of the stand, T. Additionally, for each set of impulse and pulsewidth parameters, the specific impulse was varied from 1 to over 25,000 seconds. The results are summarized in Figure 4 for an impulse of 1mN-sec. The spread in the data points represent variations in specific impulse from 1 to 25,000 sec. The magnitude of the mass loss varies with the specific impulse and has varying effects on the resulting TSMB deflection. It is interesting to note that the mass loss effect for a given impulse consistently manifests itself as a percentage of the impulse magnitude, such that smaller impulses result in proportionately smaller errors. For pulsewidths below a tenth of the natural period, the deflection appears to remain constant. For pulsewidths above a tenth of a period, an expected decrease in the deflection is evident. Figure 4 also shows that as the pulsewidth approaches the natural period of the TSMB, the range of error from the mass loss increases, which results from the accommodation to the natural period. As the pulsewidth increases, the impulse component of the trace begins to shift in phase. Similar to the superposition of waves out of phase, constructive and destructive interference can be expected. As the phases between the components begin to synchronize, constructive interference results in larger error in the magnitude of the deflection range.

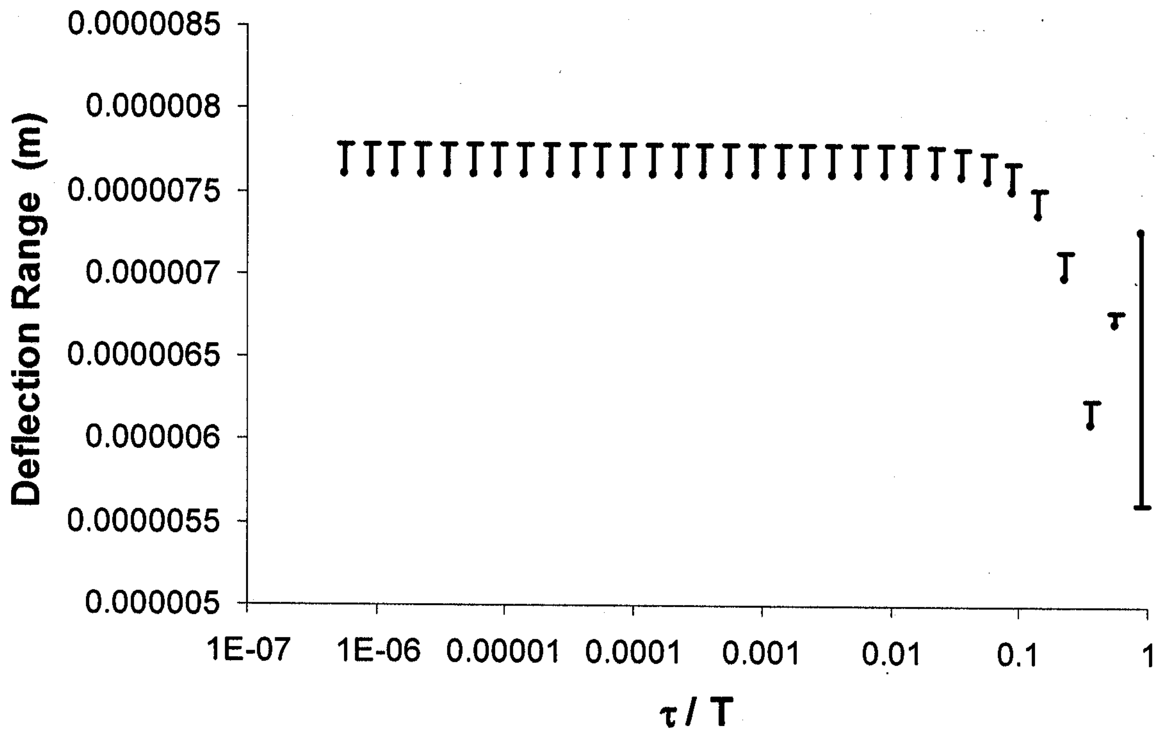


Figure 4: TSMB maximum deflection as a function of normalized impulse pulsewidth compared to the analytical model results.

Figure 5 depicts the trend of the error caused by simultaneously measuring the impulse and the corresponding mass loss. Note that Fig. 5 only includes points for pulsewidths less than 0.25T to minimize the scatter that is caused by pulsewidth effects. Above a specific impulse of approximately 2 seconds, the percentage error in the calculated deflection range is less than 0.5%. For specific impulse ranges where thrusters would typically be tested, the error is almost negligible. Therefore, the standard and simple deflection technique for measuring impulse is sufficient for the TSMB.

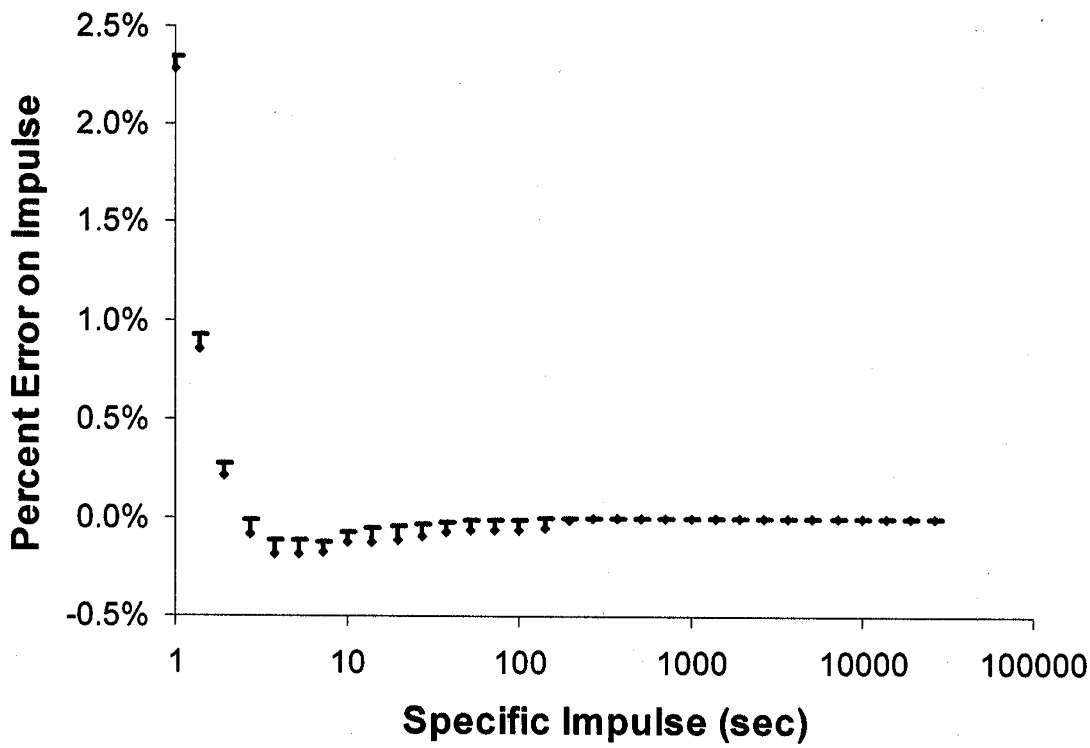


Figure 5: The error profile for impulse measurements with simultaneous mass loss measurements. This curve can be used to correct calculated impulses once the Isp of the thruster has been determined.

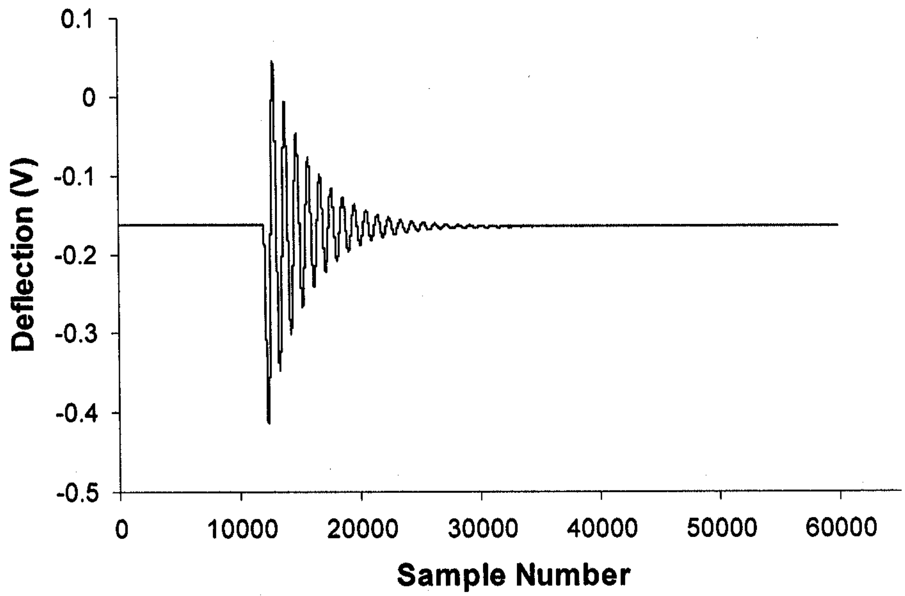
Experimental Set Up

The TSMB, shown in Fig. 1, is a torsion balance which consists of two flexure pivots which are used to support the balance and to provide a restoring and is similar to the thrust stand described by Jamision, et al.[8] The flexures have a spring constant of approximately 0.0016 Nm/deg. The TSMB is completely symmetric about the center of rotation with two armatures extending from each side of the stand. The TSMB is inertially balanced to reduce the effects of outside vibrations on the measurements. The force measurements involve the sensing of an angular displacement resulting from the torque applied to the damped rotary system. The method for detecting angular deflection is to measure the linear displacement at a known radial distance using a linear variable differential transformer (LVDT). For the forces measured in this study, the linear movement at the end of the TSMB arm is a fraction of a micrometer. Therefore, the error associated with the angular movement of the thrust stand arm is negligible. The motion of the TSMB is damped by a permanent magnet arrangement which uses eddy currents to provide a

"viscous" force. The TSMB is calibrated using an electrostatic comb system described by Selden and Ketsdever.[9]

For pulsed thruster systems, the TSMB is inverted with a horizontal axis of rotation. In this configuration, the TSMB can measure impulse and propellant mass loss simultaneously. To demonstrate the effectiveness of the TSMB, laser ablation events were investigated. Tests were configured with an Infinity Nd:YAG laser to ablate large amounts of material that were sufficient to measure. Target materials were placed on the TSMB, located in a vacuum chamber capable of maintaining background pressures of 10^{-6} Torr. Figure V shows the TSMB located inside the vacuum chamber. The Inifinty laser was configured to emit a wavelength of 532 nm, at a repetition rate of 100 Hz. A shutter was situated in the path of the laser, and a pulse generator was used to trigger the shutter, resulting in an average of 35 shots arriving at the target. On the path to the target, the laser passed through a beam splitter, allowing the power of the laser to be monitored and the number of pulses per test to be counted. Testing was performed on several engineering surfaces including machine grade Teflon, Buna, and Viton. For these tests, the average number of shots on each site was held constant, while the energy of the laser was varied between 100mJ IR to 400mJ IR. A calibration procedure, utilizing electrostatic combs[9], was conducted prior to the start of testing on each new target.

Upon completion of the tests, the data was analyzed in order to determine the impulse and mass loss of the material. This procedure required the data trace from the TSMB to undergo two different analyses. The first step was the determination of the mass lost during the ablation event. A sample trace is shown in Figure 6(a). The analysis takes the average of the data after the ablation event. This average is then used to remove any electronic (thermal) drift in the LVDT. Next, the average of the data between points before the ablation event is determined. The difference of this average to the average of the data after the ablation event is due to the change in mass of the target. The corresponding LVDT voltage change is shown in Figure 6(b). Using the calibration data from the electrostatic combs, the change in voltage can be directly correlated with a force associated with the change in target weight.



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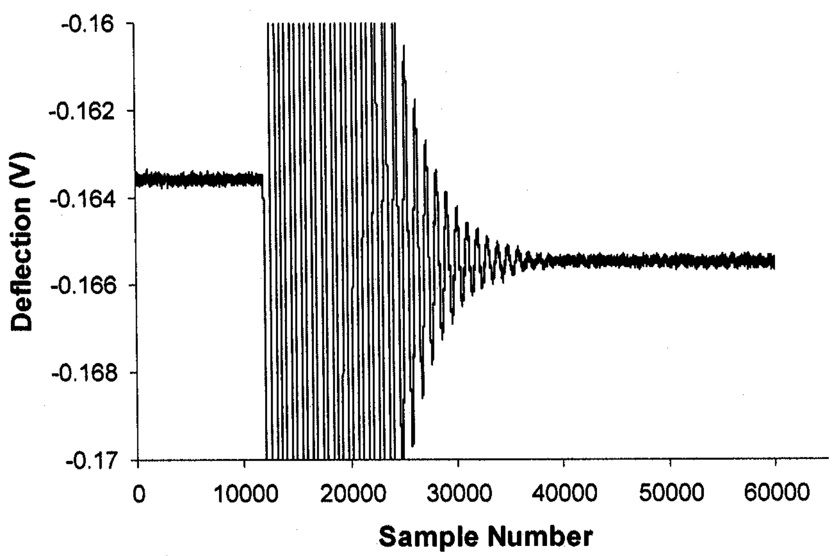


(b)

Figure 6: (a) Sample trace from TSMB. (b) Voltage change due to mass loss.

The second step of the data analysis is the determination of the impulse from the laser ablation event. This step simply took the maximum deflection of the LVDT, which occurred between the first peak and first valley of the trace. Using calibration data from the electrostatic combs, this maximum deflection can be directly correlated with an impulse.

Results and Discussion

The common measure of propulsive efficiency is the specific impulse, Isp. The specific impulse is a measure of the impulse per unit of propellant weight that is expended. From a propulsion efficiency perspective, it is desirable to get the largest impulse for the lowest mass loss, i.e. high specific impulse. In its simplest form only the total impulse measurement and mass loss measurement are required to calculate the specific impulse. Figure 7 shows the impulse and corresponding ablative mass loss for a Buna target as a function of the total laser energy delivered to the material. There is an increase in both impulse and mass loss as the laser energy increases which leads to a general increase in the specific impulse shown in Fig. 8. The scatter in the data evident in Fig. 8 may come from a variety of sources. In the calibration process, the TSMB has repeatability of less than 1% (one sigma error). The scatter in Fig. 8 is much greater than 1% indicating that the physical ablation process is most likely the reason. Each data point represents a different test at a different target material location. Surface roughness and material impurities are the most likely causes of the scatter.

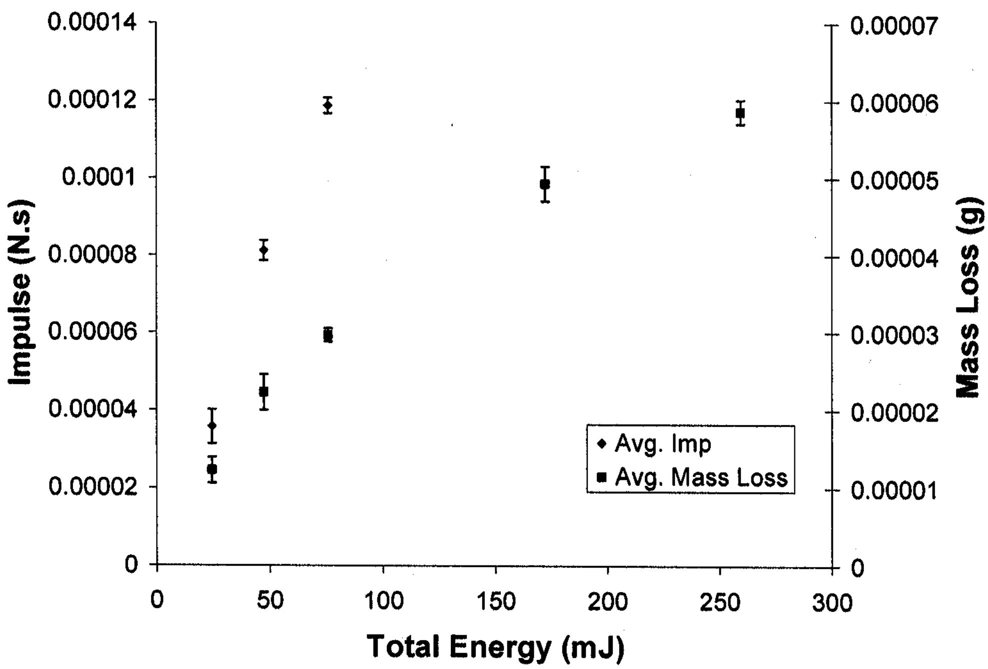


Figure 7: Impulse and mass loss for Buna target

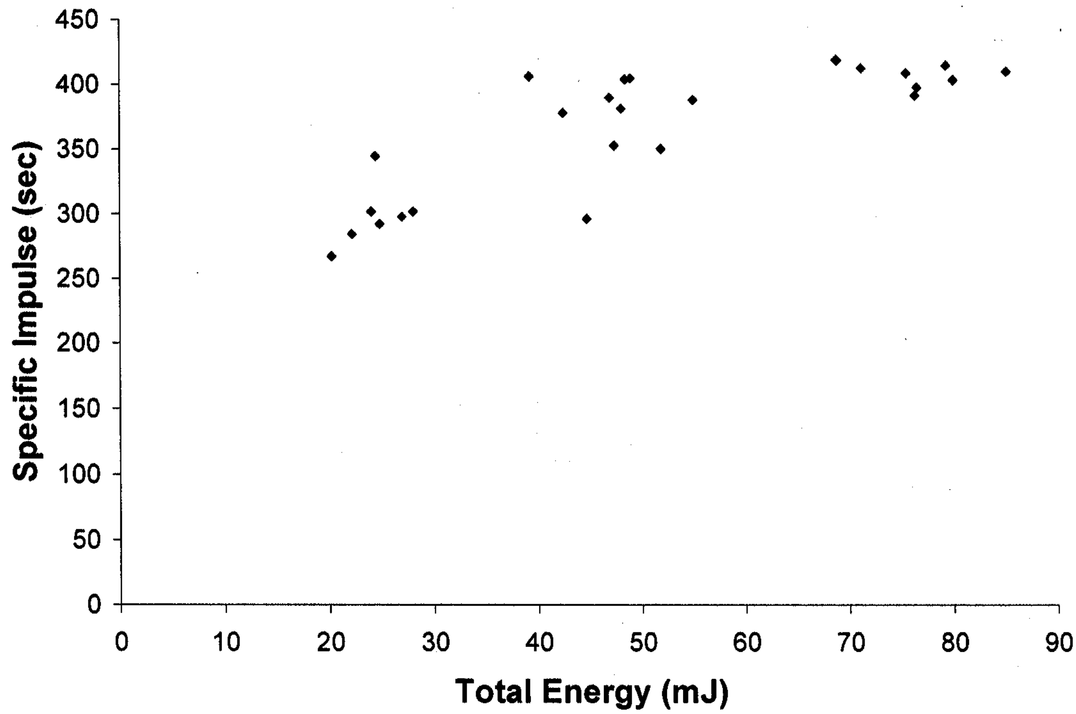


Figure 8: Specific Impulse of Buna

Figure 9 shows similar impulse and mass loss results for Viton. The specific impulse for these measurements is shown in Fig. 10. It is evident that the specific impulse increases with total laser energy up to about 50 mJ. At energies above 50 mJ the specific impulse tends to decrease. This trend can be explained by investigating the momentum coupling coefficient between the material and the incident laser beam. Phipps[10] predicts that the impulse efficiency, as measured by the momentum coupling coefficient, rapidly reaches a maximum once the ablation threshold is surpassed and then decreases with increasing laser intensity. The reduction in the efficiency can stem from several factors including the shielding of the laser beam by ablating material. The coupling coefficients as a function of laser intensity are shown in Fig. 11(a) for Viton and Buna.[11] It should be noted that both materials have relatively low ablation thresholds and correspondingly high maximum coupling coefficients. Figure 11(b) shows the coupling coefficient for mechanical grade Teflon. Note that the ablation threshold for Teflon is noticeably higher than for either Buna or Viton and the maximum coupling coefficient is lower.

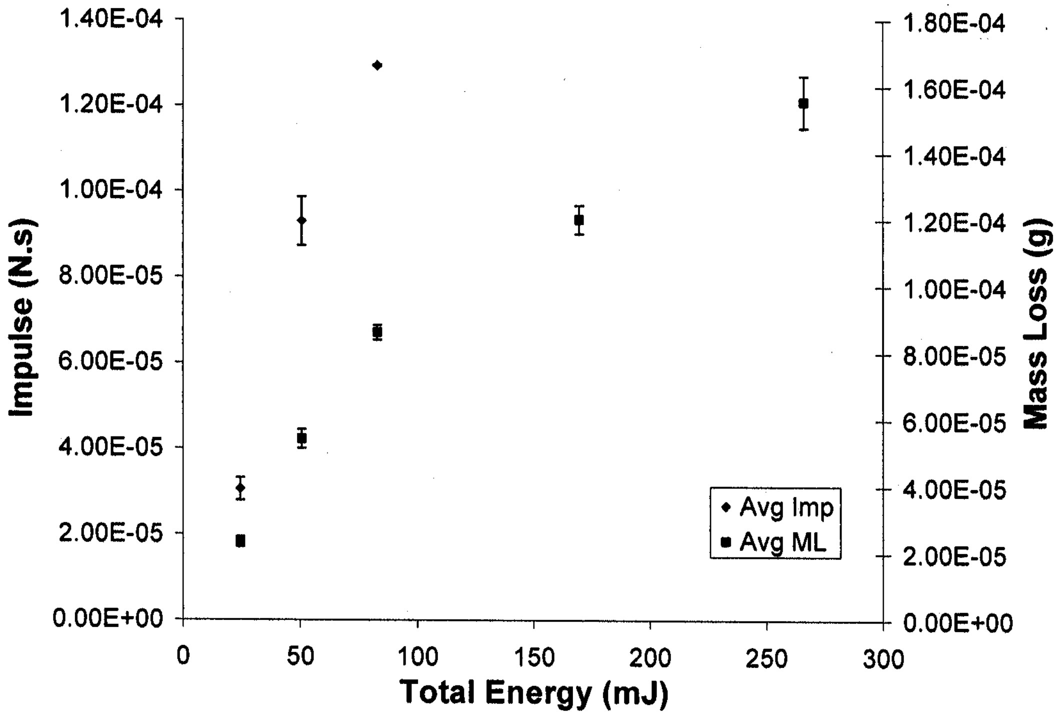


Figure 9: Impulse and mass loss for Viton

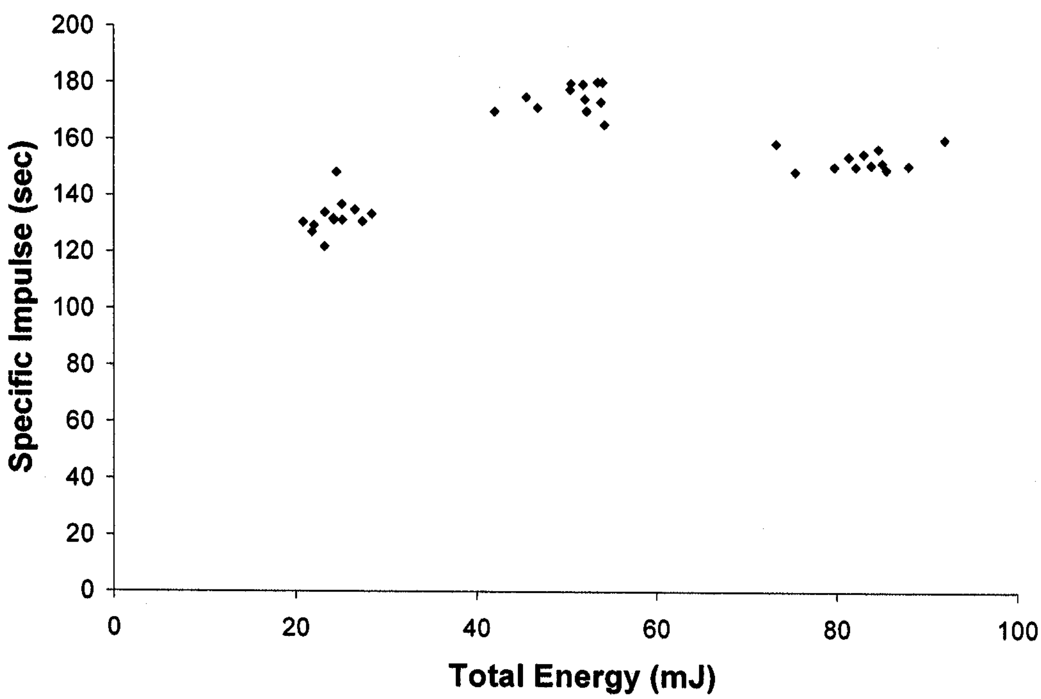
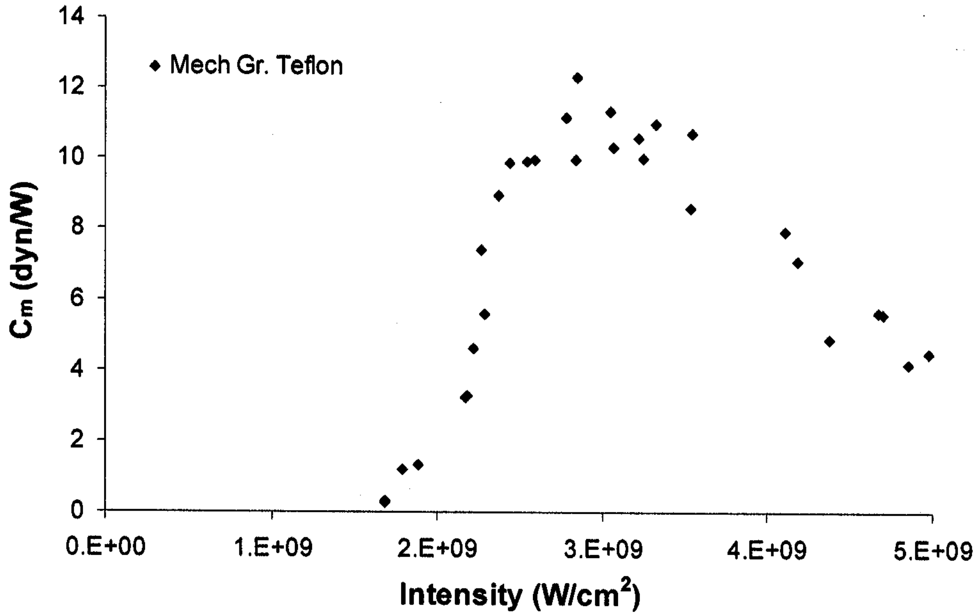
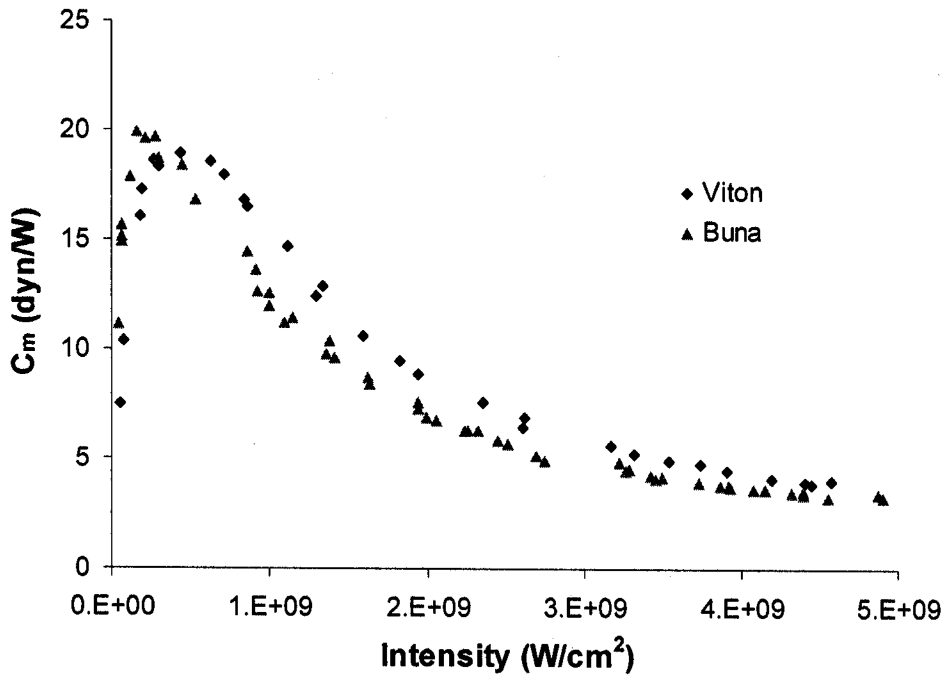


Figure 10: Specific Impulse of Viton



(a)



(b)

Figure 11: (a) Coupling coefficients for mechanical grade Teflon (b) Coupling coefficients for Viton and Buna

Figure 12 shows impulse and mass loss for machine grade Teflon with the corresponding specific impulse shown in Fig. 13. The specific impulse tends to decrease for total laser energies above about 100 mJ. The specific impulse

for Teflon is generally lower than it is for either Buna or Viton which correlates to its lower maximum coupling coefficient. The data in Figures 8, 10, and 13 shows the ability of the TSMB to consistently measure the specific impulse from laser ablation events. In these cases, both mass loss and impulse were successfully extracted from a single TSMB trace. Additionally, the trend of the data is as expected, as higher energies should result in more mass loss and larger impulses.

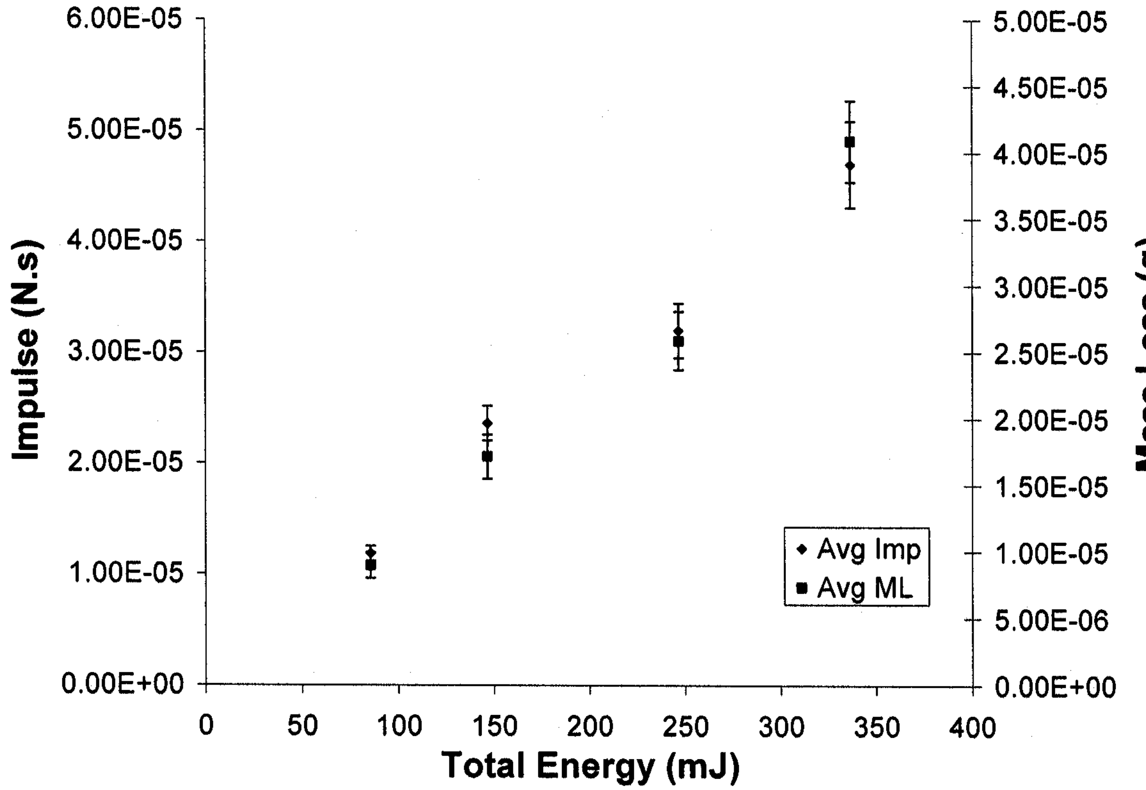


Figure 12: Impulse and mass loss for machine-grade Teflon

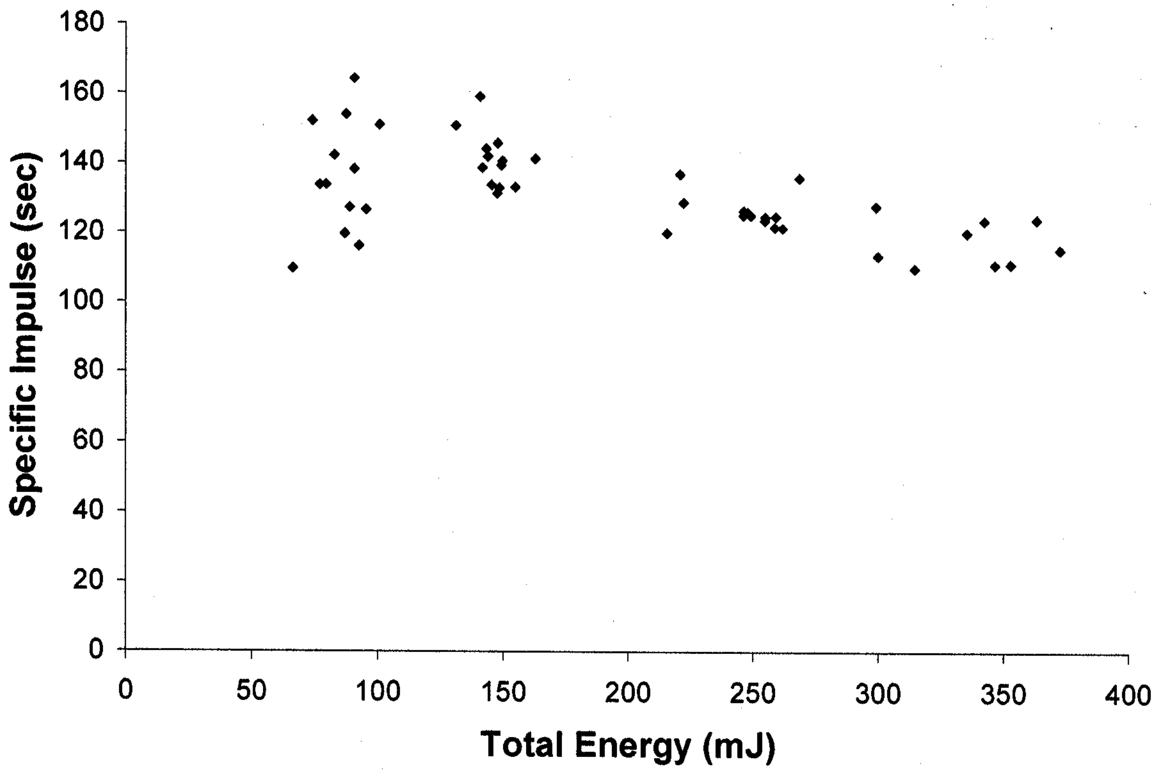


Figure 13: Specific Impulse of machine grade Teflon

Discussion

The TSMB has proven to consistently measure mass loss and impulse for laser ablation events. The ability to concurrently resolve impulse and mass loss from a single TSMB trace allows for the direct measurement of specific impulse. While some scatter is visible in the data, there are multiple factors that could contribute to this scatter. For instance, the surface roughness of the spot being ablated could vary between each test site. The TSMB demonstrated that specific impulses on the order of several hundred seconds were achievable for laser ablation thrusters on engineering surfaces and showed its usefulness as a diagnostic tool for the direct measurement of specific impulse from laser ablation thrusters for various materials. However, the model results also indicate that the TSMB will be useful for other pulsed thruster systems. Essentially, the one requirement of the thruster system is that the thruster firing time be no more than approximately one-quarter of the TSMB natural period for the inherent measurement error to remain below 0.5%. The natural period of the balance can be modified by changing either the associated

spring constant or moment of inertia allowing flexibility for a particular thruster system. The TSMB has proven its utility as a diagnostic tool for propulsion systems where the measurement of mass flow is not straightforward. Mostly these are solid propellant systems such as laser ablation thrusters, pulsed plasma thrusters, and hybrid thrusters.

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